

# Optimization Strategies for Cognition and Autonomy in Mixed Human-Robot Teams

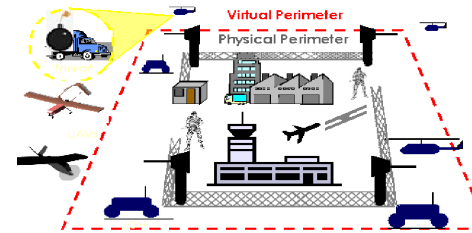
Vaibhav Srivastava and Francesco Bullo



Center for Control,  
Dynamical Systems & Computation  
University of California at Santa Barbara  
<http://motion.me.ucsb.edu>

AFOSR-DSI Data-to-Decisions & Autonomy Workshop  
RMIT University, Melbourne, Australia, July 9th and 10th, 2012

## Big Picture: Human-robot decision dynamics



Uncertain environment surveyed by human-UAV team  
(Courtesy: Prof. Kristi Morgansen)



UAV surveillance (Courtesy: <http://www.modsim.org/>)

### In New Military, Data Overload Can Be Deadly

By THOM SHANKER and MATT RICHTER

When military investigators looked into an attack by American helicopters last February that left 23 Afghan civilians dead, they found that the operator of a Predator drone had failed to pass along crucial information about the makeup of a gathering crowd of villagers.

But Air Force and Army officials now say there was also an underlying cause for that mistake: information overload.

Data is among the most potent weapons of the 21st century. Unprecedented amounts of raw information help the military determine what targets to hit and what to avoid. And drone-based sensors have given rise to a new class of wired warriors who must filter the information sea. But sometimes they are drowning.

<http://www.nytimes.com/2011/01/17/technology/17brain.html>



A surveillance operator (Courtesy: <http://www.modsim.org/>)

Vaibhav Srivastava & FB (UCSB) Cognition and Autonomy Management AFOSR-DSI Wrkshp 9jul12 1 / 27

## Two Critical Issues

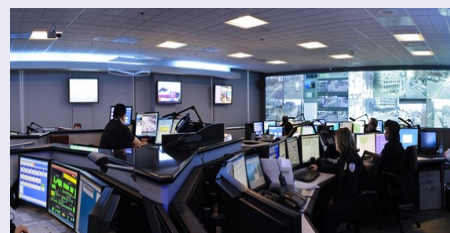
Photo courtesy: The Wall Street Journal

### Optimal information aggregation



- Which source to observe?
- Efficient search and detection
- Routing for evidence collection

### Optimal information processing



- Optimal time allocation?
- Optimal streaming rate?
- Optimal number of operators?

Cognition & Autonomy Management System (CAMS)  
to optimize human-robot team objective

## Incomplete Literature Review

### Human Decision Making

R. Bogacz, E. Brown, J. Moehlis, P. Holmes, and J. D. Cohen. The physics of optimal decision making: A formal analysis of performance in two-alternative forced choice tasks. *Psychological Review*, 113(4):700–765, 2006

R. W. Pew. The speed-accuracy operating characteristic. *Acta Psychologica*, 30:16–26, 1969

### Control of Queues

O. Hernández-Lerma and S. I. Marcus. Adaptive control of service in queueing systems. *Systems & Control Letters*, 3(5):283–289, 1983

S. Ağrali and J. Geunes. Solving knapsack problems with S-curve return functions. *European Journal of Operational Research*, 193(2):605–615, 2009

### Queues with human operator

K. Savla and E. Frazzoli. A dynamical queue approach to intelligent task management for human operators. *Proceedings of the IEEE*, 100(3):672–686, 2012

L. F. Bertuccelli, N. Pellegrino, and M. L. Cummings. Choice modeling of relook tasks for UAV search missions. In *American Control Conference*, pages 2410–2415, Baltimore, MD, USA, June 2010

N. D. Powel and K. A. Morgansen. Multiserver queueing for supervisory control of autonomous vehicles. In *American Control Conference*, Montréal, Canada, June 2012. To appear

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**Funding:** AFOSR MURI Program "Behavioral Dynamics in Mixed Human/Robotics Teams" 5/07-6/12

## Attention Allocation Strategies

V. Srivastava, R. Carli, C. Langbort, and F. Bullo. Attention allocation for decision making queues. *Automatica*, February 2012. Submitted

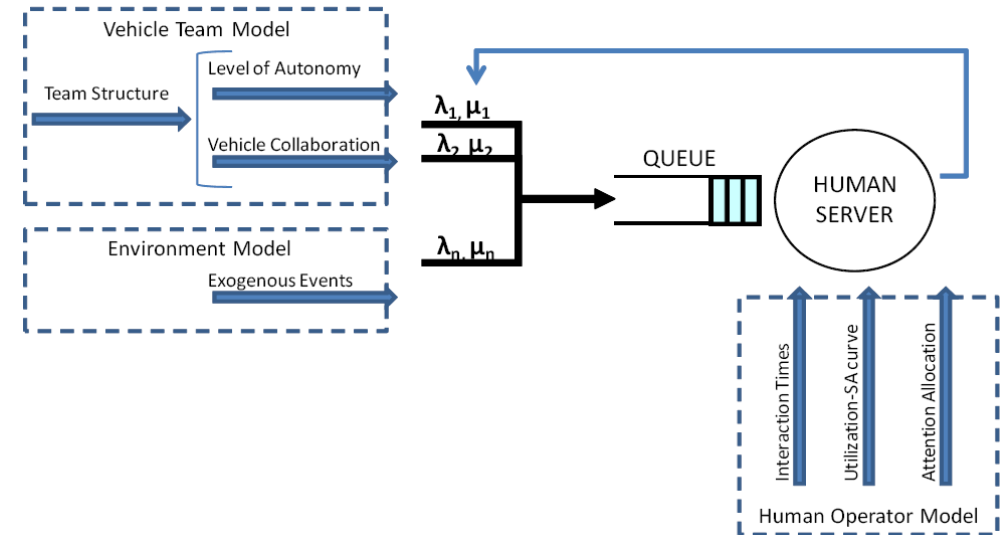
V. Srivastava, A. Surana, and F. Bullo. Adaptive attention allocation in human-robot systems. In *American Control Conference*, pages 2767–2774, Montréal, Canada, June 2012

V. Srivastava, C. J. Ho, M. P. Eckstein, and F. Bullo. Handling operator overload: An experimental study. In preparation

## Search and Surveillance Strategies

V. Srivastava, F. Pasqualetti, and F. Bullo. Stochastic surveillance strategies for spatial quickest detection. *International Journal of Robotics Research*, April 2012. Submitted

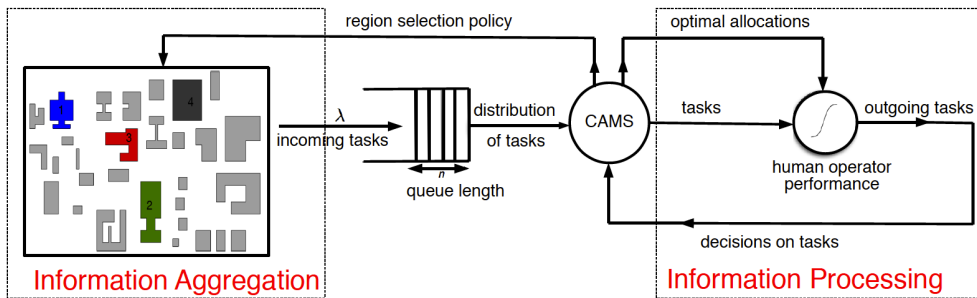
V. Srivastava, K. Plarre, and F. Bullo. Randomized sensor selection in sequential hypothesis testing. *IEEE Transactions on Signal Processing*, 59(5):2342–2354, 2011



General vehicle team and human operator interaction model

C. Nehme, B. Mekdeci, J. W. Crandall, and M. L. Cummings. The impact of heterogeneity on operator performance in futuristic unmanned vehicle systems. *The International C2 Journal*, 2(2):1–30, 2008

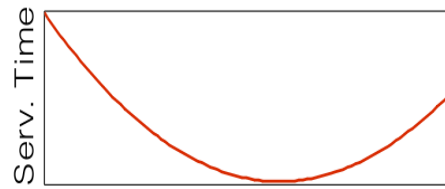
# Cognition and Autonomy Management System



- Information collection and aggregation by robotic network
- Information processing and decision making by human operator
- Based on tasks in queue and estimated cognitive state, CAMS **specifies the time** the operator should spend on each task
- Based on the operator's decisions and world estimate, the CAMS collects information from the **most pertinent source**

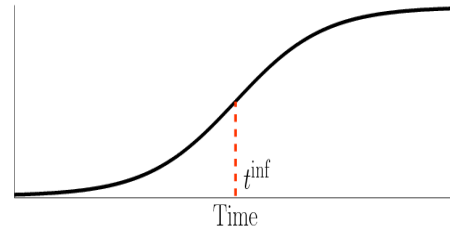
# Outline

- 1 Introduction
- 2 Topic 1: Information Processing
- 3 Topic 2: Information Aggregation
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- 5 Conclusions



Utilization Ratio  
Yerkes Dodson effect

Yerkes-Dodson 1908



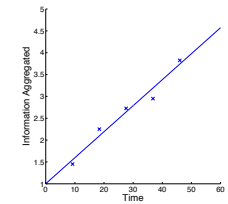
Evolution of probability of detection

Pew '68

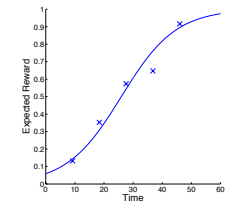
- 1 operator utilization ratio = linear dynamical system  
expected (unforced) service time = convex function of utilization  
Y-D curve well-established, e.g., validated by Savla et. al. '10
- 2 the evidence for decision making evolves as a drift-diffusion process  
the probability of the correct decision is a sigmoid function of time



- task = spot the differences
- expected # detected differences is linear function of time (DDM)
- probability to detect more than 60% diffs is sigmoid (threshold-based decision making)



Information aggregation satisfy DDM

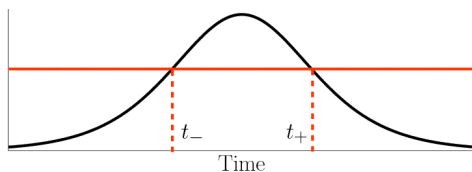


Probability of correct decision is sigmoid

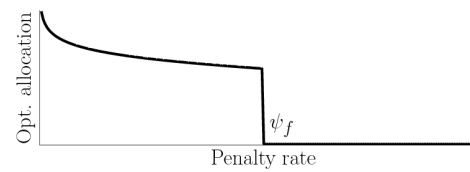
## Implications of Sigmoid Performance

### Sigmoid function and linear penalty

$$\text{maximize}_{t \geq 0} f(t) - \psi t$$



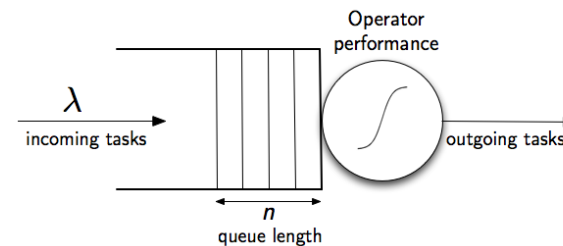
Derivative of a sigmoid function



Optimal allocation v/s penalty rate

- Optimal allocation jumps down to zero at critical penalty rate
- Jump creates combinatorial effects

## Dynamic Queue with Penalty and Situational Awareness I



- Tasks arrive as a Poisson process with rate  $\lambda$
- Task  $\gamma$  sampled from a distribution  
reward  $w_\gamma$ , sigmoid params (inflection, slope), penalty rate  $c_\gamma$
- **State variables:** queue length  $n_\ell$  and utilization ratio  $x_\ell$  at stage  $\ell$
- Unforced service time = Y-D law  $S_\gamma(x)$
- **Decision variables:** duration allocation  $t_\ell$ , rest time  $r_\ell$ , binary  $z_\ell$

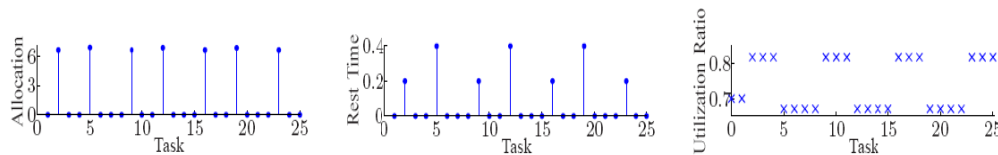
## Average Reward

$$\max_{z_\ell, t_\ell \geq z_\ell S(x_{\ell-1})} \lim_{L \rightarrow \infty} \frac{1}{L} \sum_{\ell=1}^L z_\ell \left( \mathbb{E}[w_{\gamma_\ell} f_{\gamma_\ell}(t_\ell)] - \bar{c} \mathbb{E}[n_\ell](t_\ell + r_\ell) - \frac{\bar{c} \lambda (t_\ell + r_\ell)^2}{2} \right)$$

## System Dynamics

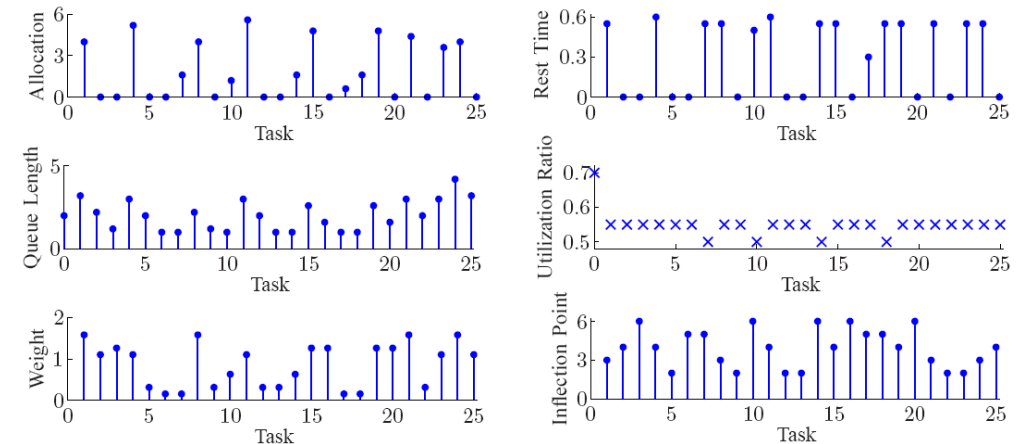
**Queue length:**  $\mathbb{E}[n_{\ell+1}] = \mathbb{E}[\max\{1, n_\ell - 1 + \text{Poisson}(\lambda z_\ell(t_\ell + r_\ell))\}]$ ,

**Utilization:**  $x_{\ell+1} = (1 - e^{-\frac{t_\ell z_\ell}{\tau}} + x(\ell) e^{-\frac{t_\ell z_\ell}{\tau}}) e^{-\frac{r_\ell z_\ell}{\tau}}$ ,  $x_\ell \in [x_{\min}, x_{\max}]$



Certainty Equivalent Solution

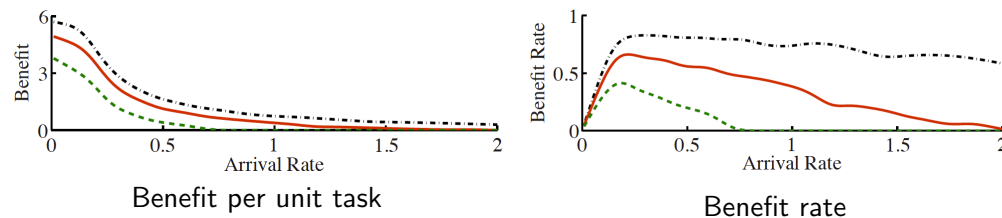
## Optimal Allocations and Rest Time



Receding Horizon Policy

# Illustrative Example II

## Reward versus Arrival Rate

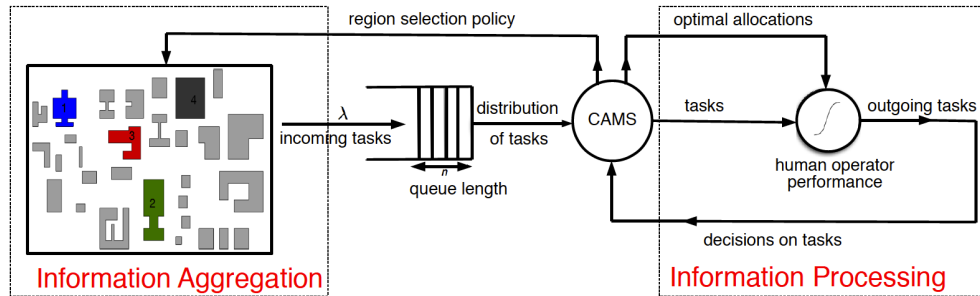


## Optimal arrival rate

- Switching occurs when operator is expected to be always non-idle
- Designer may pick desired accuracy on each task to design arrival rate

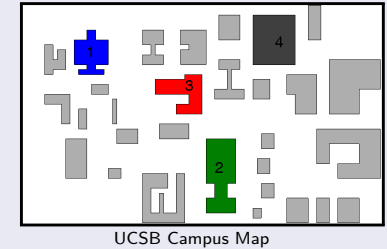
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- Based on tasks in queue and estimated cognitive state, CAMS **specifies the time** the operator should spend on each task
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- $N$  regions, arbitrary # anomalies
- an ensemble of CUSUM algorithms
- $T_k = \text{collection} + \text{transmission} + \text{processing time at region } k$
- $d_{ij} = \text{distance between region } i \text{ and } j$



## Spatial Quickest Detection

- 1 at iteration  $\tau$ , pick a region  $k$  from stationary distribution  $\mathbf{q}$
- 2 go to region  $k$  and collect evidence  $y_\tau$
- 3 update CUSUM statistic for region  $k$

$$\Lambda_k = (\Lambda_{k-1} + \log(f_k^1(y_\tau)/f_k^0(y_\tau)))^+$$

- 4 declare an anomaly at region  $k$  if  $\Lambda_k > \eta$

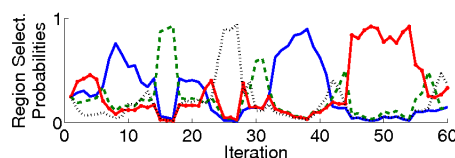
## Spatial Quickest Detection: Detection Delay

### Expected detection delay at region $k$

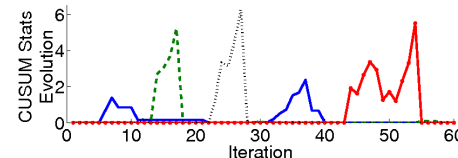
$$\mathbb{E}[\text{delay}_k(\mathbf{q})] = \frac{e^{-\eta} + \eta - 1}{q_k \mathcal{D}(f_k^1, f_k^0)} (\mathbf{q} \cdot \mathbf{T} + \mathbf{q} \cdot D\mathbf{q})$$

### Two stage quickest detection strategy

- 1 pick optimal  $\mathbf{q}^* = \text{argmin} \sum_{k=1}^N \pi_k^1 \mathbb{E}[\text{delay}_k(\mathbf{q})]$
- 2 adapt  $\mathbf{q}^*$  with the evidence collected at each stage



Region Selection Probability

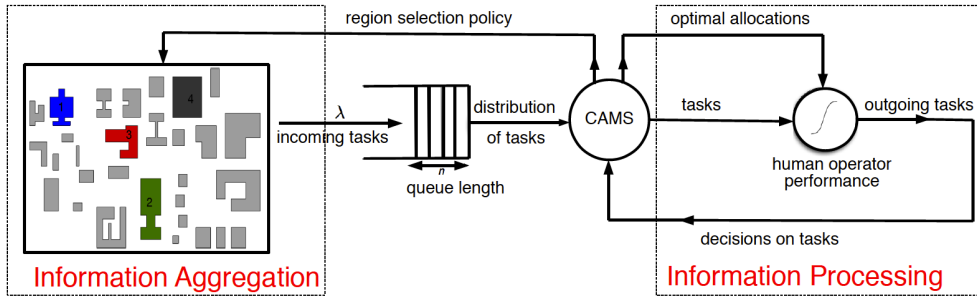


Likelihood of Anomaly

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- Based on tasks in queue and estimated cognitive state, CAMS **specifies the time** the operator should spend on each task
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- human operator allocates time  $t$  to a task and decides on presence/absence of anomaly
- decision in a **Bernoulli** random variable with

$$\mathbb{P}(\text{success}|t) = \begin{cases} f_k^1(t), & \text{if an anomaly is present,} \\ f_k^0(t), & \text{if no anomaly is present.} \end{cases}$$

## Spatial Quickest Detection

- 1 at stage  $\ell$ , pick a region  $k$  from stationary distribution  $\mathbf{q}$
- 2 go to region  $k$  and collect evidence  $y_\ell$  and **decision**  $\text{dec}_\ell \in \{0, 1\}$
- 3 update CUSUM statistic for region  $k$

$$\Lambda_k = (\Lambda_{k-1} + \log(\mathbb{P}(\text{dec}_\ell|t_\ell, \text{anomaly})/\mathbb{P}(\text{dec}_\ell|t_\ell, \text{no anomaly})))^+$$

- 4 declare an anomaly at region  $k$  if  $\Lambda_k > \eta$

## Simultaneous Information Aggregation and Processing I

### Critical Issue:

human decisions are not i.i.d.

⇒ **no closed form delay expression**

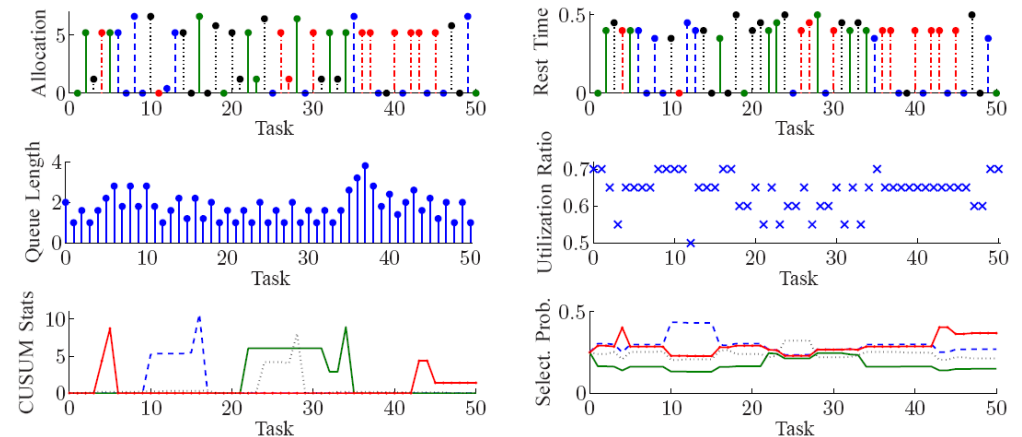
### Upper Bound

$$\mathbb{E}[\text{delay}_k] \leq \frac{e^{-\eta} + \eta - 1}{q_k D_{\min}(k)} (\mathbf{q} \cdot \mathbf{T} + \mathbf{q} \cdot D\mathbf{q})$$

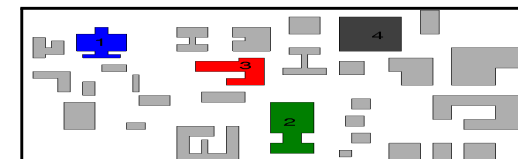
### Adaptive Policy with Human Feedback

- 1 determine  $\mathbf{q}^*$  and sample regions
- 2 set operator performance at region  $k$   
$$f_k(t) = \pi_k f_k^1(t) + (1 - \pi_k) f_k^0(t)$$
- 3 determine optimal allocation and rest time
- 4 update CUSUM statistic using operator's decision
- 5 go to step 1.

## Simultaneous Information Aggregation and Processing II



Optimal Policies



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### Conclusions

- disciplines: human cognitive performance models, dynamics vehicle routing, decision making, dynamic optimization
- *simultaneous information aggregation and processing* architecture
- incorporation of cognitive / situational awareness / autonomy
- an adaptive strategy that collects evidence from regions with high likelihood of anomalies and optimally processes it

### Future Directions

- experimental validation of models [ongoing] and of architecture
- incorporation of fatigue, learning and other cognitive models
- re-queuing of tasks, preemptive queues and more general scenarios
- dynamic anomalies and more complex detection tasks
- multi-vehicle, multi-operator, single-operator multitasking, heterogeneous scenarios

## 3rd IFAC Workshop on Distributed Estimation and Control in Networked Systems

NecSys'12, September 14-15, 2012, Fess Parker's Doubletree Resort, Santa Barbara, California



### Relevant Dates and Proceedings

- Submissions to NecSys 12 are open as of March 25. Please, read the [Information for Authors](#).
- Extended Papers submission deadline: April 30, 2012
- Notice of acceptance: June 14, 2012
- Final version due: July 15, 2012
- Early registration deadline: July 15, 2012
- Hotel registration deadline: August 13, 2012